Improvement of a Single Node Indoor Localization System

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Abstract. With the development of wireless communication technologies and the Internet, the application scenarios of positioning technologies are becoming more and more abundant. Therefore, the demand for location-based services is increasing greatly. Moreover, due to the widespread deployment of commercial WIFI devices, a WIFI-based localization system is very promising. This paper focuses on the localization algorithms utilizing Channel State Information (CSI) based on a conventional MUSIC algorithm in a single-node indoor localization system. However, the conventional MUSIC algorithm searches all the peaks in spatial spectrum. It requires enormous computation and thus is unsuitable for accurate positioning applications. This paper is intended to improve the algorithm in terms of positioning accuracy and computational complexity. Numerical results show that the proposed algorithm can improve the positioning accuracy and reduce computational complexity.

Keywords: Single-node indoor localization · Band splicing · Direct search

1 Introduction

As indoor environment become more and more complex, the demand for location-based services is increasing greatly. At present, indoor positioning systems mainly use wireless sensor networks for positioning, including Bluetooth, Zigbee, WIFI and so on. With the promotion of the IEEE 802.11 protocol, the WIFI has been widely used thanks to the features of low cost, high transmission rate and convenient connection [1]. Therefore, the design of indoor positioning system based on WIFI protocol has gradually become a research hotspot.

At present, the positioning technology based on WIFI can be mainly divided into two parts: position resolution based on geometry and matching positioning based on position fingerprint [2]. The positioning algorithm based on geometric model needs to calculate the time of arrival (TOA) or angle of arrival (AOA) transmitted by the terminal to AP, and then use the geometric model for positioning. The position fingerprint algorithm can be mainly divided into two stage. The first stage is called the offline stage. In this stage, we need to place several APs in the location area, then divide the location area into several subareas, measure the received signal strength indication (RSSI) in each subarea, and map all the RSSI to the location information. The second stage is called the online stage. In this stage, receive RSSI message online and find out the most similar fingerprint location as a result of the positioning. However, the

J. Zheng et al. (Eds.): ADHOCNETS 2019, LNICST 306, pp. 208–219, 2019.
https://doi.org/10.1007/978-3-030-37262-0_17

position fingerprint algorithm requires large number of APs and needs to collect information offline, which brings inconvenience to system deployment. And no matter which position fingerprint algorithm, RSSI is generally used as the basis for positioning. But, RSSI is susceptible to many factors in a typical indoor environment [3]. This may cause a large error in the positioning result. We need to use channel state information (CSI), which can carry detailed information, instead of RSSI [4].

The channel state information is the channel attribute in communication, and can describe the signal amplitude and phase information of each subchannel of the OFDM modulated signal. So, the CSI contains more fine-grained information than the RSSI and get accurate results in indoor positioning.

From the perspective of system construction and maintenance, traditional indoor positioning systems require more than one APs, and some systems require pre-deployment. Indoor positioning systems are limited for scenarios where multiple APs cannot be placed and the environment changes rapidly over time.

Based on the problems existing in conventional indoor positioning systems, this paper proposes a single node indoor localization system use channel state information. Select the phase of the received CSI to calculate the position. Using the Multiple Signal Classification (MUSIC) algorithm to estimate the AOA in TOA [5]. Finally, it is proposed that band splicing and direct search algorithm respectively improve the positioning accuracy and reduce the computational complexity of the algorithm.

2 System Model

2.1 Single Node Indoor Localization System Model

In a single node indoor localization system, in order to calculate the position of the terminal, it is necessary to know the distance d and angle of the θ AP to terminal [6]. The estimation of the angle can be obtained by estimating the spatial spectrum of the antenna array, and in order to calculate the distance, it is necessary to obtain the signal transmission time, and then multiply by the propagation speed of the electromagnetic wave. The single node indoor localization model is shown in Fig. 1.

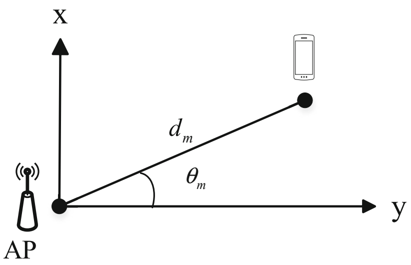

Fig. 1. Single node indoor localization model

2.2 Theoretical Derivation

In the indoor environment, the transmitted signal will be reflected and scatter through the wall to reach the receiving AP with multipath signals of different delays and amplitudes. Therefore, the frequency response of the channel is shown in Eq. (1).

$$H_i = \sum_{p=1}^{L} a_{i,p} e^{-j2\pi f_i \tau_{i,p}} \tag{1}$$

By performing discrete Fourier transform, the channel impulse response (CIR) in the corresponding time domain can be obtained, and the power delay distribution (PDP) can be obtained by squared, as shown in Eq. (2).

$$P_i(\tau) = E\left[|h_i(\tau)|^2\right] = E\left[\left|\sum_{p=1}^{L} a_{i,p}\delta(\tau - \tau_{i,p})\right|^2\right] \tag{2}$$

The power delay distribution calculated by using the received channel state information matrix is as shown in Fig. 2.

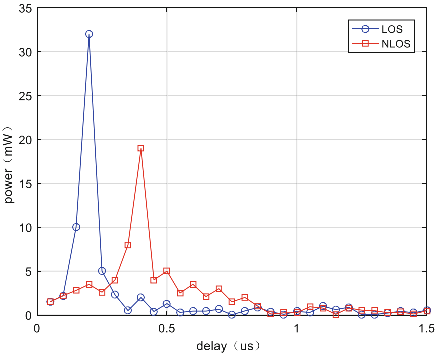

Fig. 2. Power delay distribution

The first peak in the power delay can be found as the direct path, and the corresponding delay time can be used as the transmission delay to calculate the distance. However, since multiple signal peaks overlap together in a complicated indoor environment, which causes the first peak to be indistinguishable, the performance of the transmission delay calculation based on the power delay is poor. Given the above reasons, in this paper, we use the phase of the channel state information to calculate the signal transmission delay.

Compared to RSSI, the channel state information contains amplitude and phase information of the subcarrier. Assuming that there is no multipath signal, the phase of subcarrier i is as shown in Eq. (3).

$$\phi_i = \xi + \tau \cdot (f_0 + \Delta f \cdot k_i) \tag{3}$$

Where ξ represents the initial phase and τ represents the transmission delay. For any two subcarriers, the phase difference is as shown in Eq. (4).

$$\Delta\phi = \tau \cdot \Delta f(k_i - k_j) \tag{4}$$

It can be seen that the phase difference of the subcarriers is proportional to the transmission delay, so the transmission delay can be solved by the phase difference. However, due to the multipath effect in the indoor environment, it is necessary to identify the multipath of the received phase, and the same problem exists for the calculate the angle of arrival. This paper proposes using the MUSIC algorithm to calculate the transmission delay and angle of arrival.

3 MUSIC Algorithm

3.1 Theoretical Basis

The basic idea of MUSIC is to decompose the covariance matrix of the array to obtain the signal subspace and the noise subspace, and use the orthogonality of the two subspaces to estimate the parameters of the signal. The theoretical model is shown in Fig. 3.

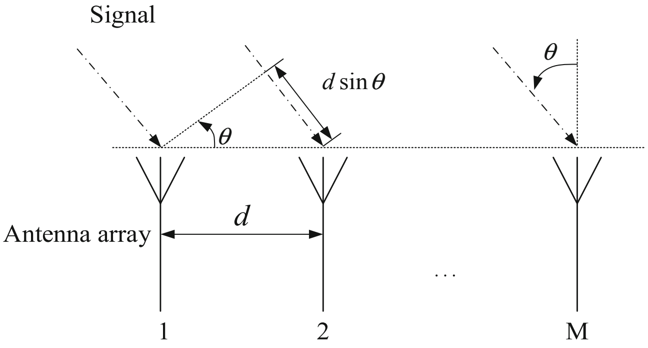

Fig. 3. The model of MUSIC algorithm

In the figure, the number of antennas is M, and the spacing between two adjacent antennas is d. The number of OFDM subcarriers is 30. It is assumed that the signal is reflected and scatter by the wall and becomes L multipath to reach the positioning AP. For different received signals, their phase offsets on different receiving antennas are related to the carrier frequency and the transmission distance to different antennas, while the difference of transmission distance is determined by the angle of arrival. Therefore, the phase difference due to the difference between the AOA and the carrier frequency is shown in Eq. (5).

$$a_{m,i}(\theta_p, \tau_p) = \Phi_{\theta_p}^{m-1}\Omega_{\tau_p}^{i-1} = e^{-j2\pi(m-1)d\sin\theta_p \cdot f/c} e^{-j2\pi(i-1)\Delta f \cdot \tau_p} \tag{5}$$

As long as $a(\theta, \tau)$ can be calculated based on the phase information of the received CSI, the angle θ and delay τ can be obtained. The steering matrix can be solved by using the orthogonality of the signal subspace and the noise subspace. Angles and delays are obtained by constructing a spatial spectrum and searching for peaks in the spatial spectrum. The definition of spatial spectrum is shown in Eq. (6)

$$P(\theta, \tau) = \frac{1}{a^H(\theta, \tau)E_N E_N^H a(\theta, \tau)} \tag{6}$$

The denominator part of the equation is the product of the steering matrix and the noise matrix. When the steering matrix is orthogonal to the noise matrix, the denominator is zero, but there is a minimum due to the presence of noise. By changing the angle and delay, we can find the peak of the spatial spectrum, and then obtain the arrival angle and transmission delay of the multipath signal. Detailed solution process in [7].

3.2 Insufficient in the Algorithm

3.2.1 Computational Complexity of the Algorithm

In the MUSIC algorithm introduced in Sect. 3.1, in addition to the calculation of the matrix, it is necessary to search the angle and delay peak in spatial spectrum. In order to ensure that the peaks of different multipaths can be accurately distinguished, it is necessary to reduce the search step size to improve the resolution of the spatial spectrum. It is assumed that the AOA is 1° in steps and the search range is from −90° to 90°. The transmission delay is in steps of 1 ns, and the search range is from 0 ns to 100 ns (the corresponding distance is 0.3 m in steps, and 0 to 30 m is the search range). In order to find all the peaks, it at least calculates 18, 180 points in the spatial spectrum and make thousands of comparisons.

Moreover, during the positioning, it is only necessary to find the peak with the smallest transmission delay as the direct path to calculate the position. Generally, it is not necessary to know the AOA and transmission delay corresponding to all peaks, so it is unnecessary to perform the two-dimensional peak search for all the peaks. Therefore, reducing the computational complexity of the single-point indoor positioning algorithm based on MUSIC and reducing the time of spatial spectrum search is an urgent problem to be solved.

3.2.2 Positioning Accuracy of the Algorithm

Although the resolution of the peak can be increased by reducing the search step size, the resolution is limited by this method, so it is necessary to look for the factors affecting the peak resolution from the algorithm itself.

We take the derivative of Eq. (5) and then get Eqs. (7) and (8).

$$\frac{\partial \Phi_{\theta}^{m-1}}{\partial \theta} = -j2\pi d(m-1) \cdot \frac{\cos\theta}{c} \cdot f \cdot \Phi_{\theta}^{m-1}, m \in [1, M] \tag{7}$$

$$\frac{\partial \Omega_{\tau}^{i-1}}{\partial \tau} = -j2\pi(i-1) \cdot \Delta f \cdot \partial \Omega_{\tau}^{i-1}, i \in [1, N_{sub}] \tag{8}$$

It can be seen that the resolution of the spatial spectrum depends on factors such as the number of antennas in the antenna array, adjacent antenna spacing, subcarrier frequency and number of subcarriers. Since the wireless network card capable of receiving CSI only has an Intel 5300 network card, and its antenna interface has only three, it is impossible to increase the spatial spectral resolution by increasing the number of antennas. Meanwhile, in the actual antenna array, the interval between the antennas is fixed. Therefore, it is also impossible to increase the spatial spectral resolution by increasing the spacing between the antennas. Therefore, the spatial spectrum resolution can be improved by increasing the carrier frequency, subcarrier frequency interval and the number of acquired subcarriers.

4 Improvement of Accuracy and Complexity

4.1 Band Splicing Improve Accuracy

4.1.1 Band Splicing

Section 3.2 analyzes how to improve the resolution of the spatial spectrum. Whether increasing the subcarrier frequency interval or increasing the number of acquired subcarriers, it is necessary to increase the bandwidth of the received CSI, that is, to get more phase information of CSI in continuous frequency bands. Under the 802.11n protocol, the channel division corresponding to the 2.4 GHz band is shown in Fig. 4.

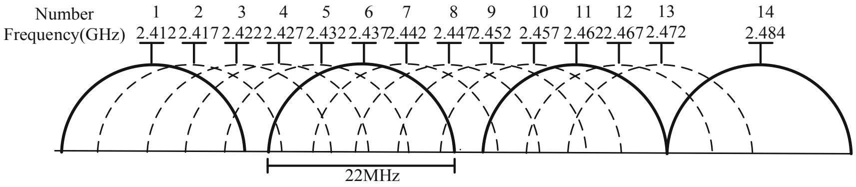

Fig. 4. Channel division at 2.4 GHz

Receive the phase of 1, 4, 7, and 10 channels by changing the receiving center frequency of the WIFI. And splice the phase information of four channels by using frequency band splicing. The method of spectrum splicing is shown in the Fig. 5.

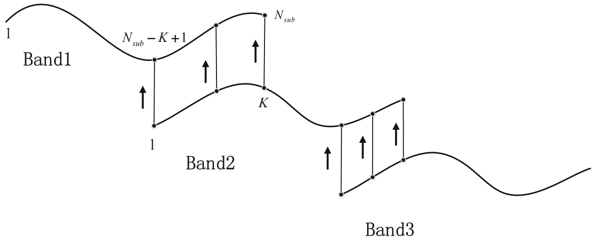

Fig. 5. The method of spectrum splicing

Band splicing can be divided into 3 steps:

(1) Change the channel where the AP is located, and receive 4 sets of channel state information under the channels with the center frequency of 2.412 MHz, 2.427 MHz, 2.442 MHz, 2.457 MHz, respectively.
(2) Calculate the relative phase difference of the subcarriers overlapping in the adjacent channel, and use the average value of the difference as the upward translation value of the latter channel phase information, wherein the phase of the overlapping portion takes the mean of the two channel phase values.
(3) Repeat step 2 until all phase are stitched together and phase band splicing is shown in the Fig. 6.

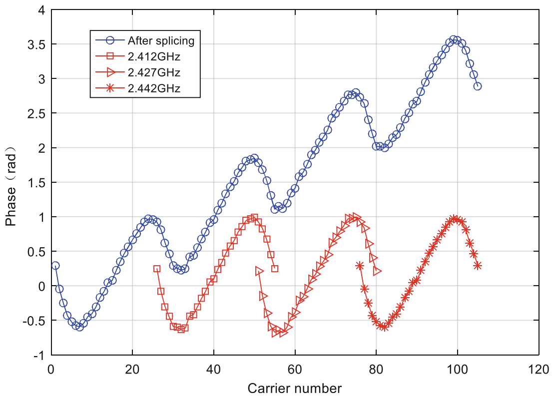

Fig. 6. Phase after band splicing

4.1.2 Spatial Spectrum

After band splicing, the bandwidth is increased from 20 MHz to 65 MHz. There are two ways to increase the resolution of the spatial spectrum. The first is to increase the number of subcarriers, and to use the phase information of all 105 subcarriers; the second is to increase the subcarrier spacing, extract 30 subcarriers from 105 subcarriers at equal intervals, and use the phase information of the extracted subcarriers. Detailed mathematical derivation can refer to the literature [8]. The spatial resolution after band spliced are shown in the Figs. 7, 8 and 9.

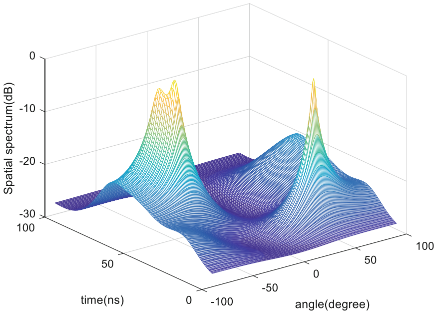

Fig. 7. Spatial spectrum without band splicing

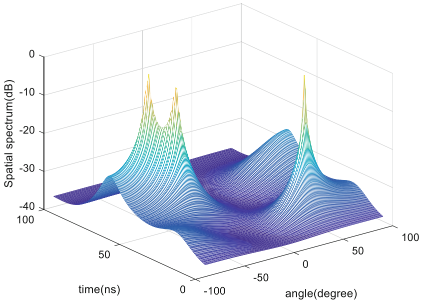

Fig. 8. Increasing the number of subcarriers

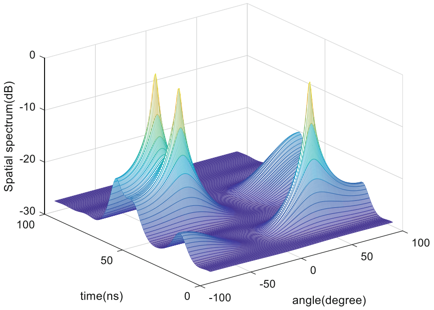

Fig. 9. Increase subcarrier frequency spacing

As can be seen from the figure, after the band is spliced, the resolution of the spatial spectrum is improved, more peaks can be discerned, and positioning error can be also reduced.

4.2 Reduce Computational Complexity

In the single-node indoor positioning system based on the MUSIC algorithm, the angle and delay of the multipath signal are mainly estimated by using the phase difference of the received CSI. The transmission delay is estimated by using the phase difference of different frequency subcarriers in the same antenna, while. The angle is estimated by the phase difference of the same frequency subcarriers received by adjacent antennas in the antenna array. Therefore, the angle and time delay estimates can be split, and one of the variables can be estimated by constructing a one-dimensional spatial spectrum. Calculate another variable by substituting the estimated value into a two-dimensional spatial spectral formula. In short, the meaning of direct search is to use one part of information to estimate one of the two variables, than to estimate another variable in the spatial spectrum of all the information.

First, estimate the transmission delay by using 30 subcarriers which received by the same antenna. The method of estimating the delay is the same as that introduced in 3.1, except that the dimension of the spatial spectrum is one-dimensional.

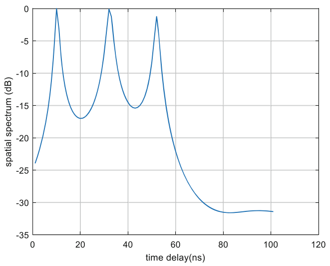

Fig. 10. Spatial spectrum of time delay

There are three peaks that can be clearly distinguished in the Fig. 10, and the corresponding delay is the multipath transmission delay. After selecting the minimum delay as the transmission delay of the direct path, multiply it by the speed of the electromagnetic wave to get the distance. For the receiving angle, we need to substitute the delay into the formula (5), and calculate the peak to get the angle. The spatial spectrum after substituting the delay is shown in Fig. 11.

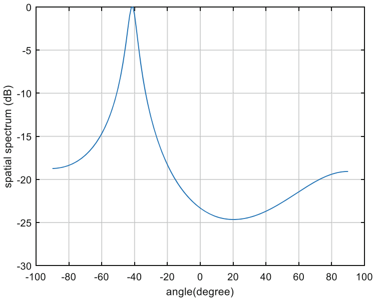

Fig. 11. Spatial spectrum of angles

The direct search algorithm decomposes the two-dimensional spatial spectrum and reduces the computational complexity. However, for the estimation of the delay, a one-dimensional peak search is still needed. In this paper, the Root-MUSIC algorithm and the ESPRIT algorithm are used to avoid the peak search.

The Root-MUSIC algorithm mainly obtains delay by constructing and solving high-order polynomials. The ESPRIT algorithm needs to construct two equally spaced sub-arrays and then use the rotation invariance of the sub-array to calculate the delay. Both methods avoid peak search and reduce computational complexity. However, the positioning accuracy may be affected when the amount of calculation is reduced. However, when the amount of calculation is reduced, the positioning accuracy may be affected. Figure 12 shows the variation of the positioning error of different algorithms with the change of SNR.

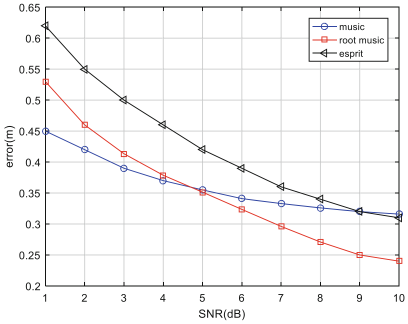

Fig. 12. Positioning error varies with SNR

It can be seen that under the low SNR, the positioning error of the MUSIC algorithm is relatively small, and under the high SNR, the positioning error of the Root-MUSIC algorithm is relatively small. But overall, the MUSIC algorithm is relatively stable.

This paper selects a test point which is located at a distance of 7 M. The following are the test results.

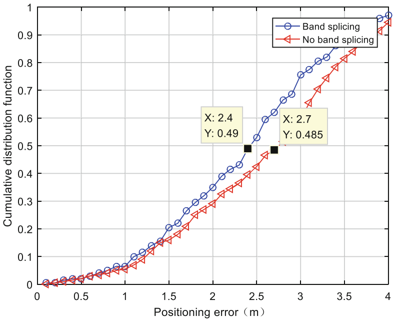

Fig. 13. Positioning error

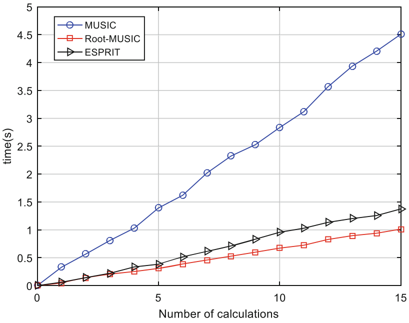

Fig. 14. Time required for operation

As shown in Fig. 13, the positioning error is about 2.4 m when there is no band splicing, and the positioning error after band splicing is about 2.7 m. Figure 14 shows the time required for the three algorithms to run as the number of calculations increases. Therefore, the positioning error of the single-point indoor positioning system is about 2.7 m. The positioning accuracy of single-node indoor positioning system can be improved by frequency band splicing and algorithm complexity can be reduced by direct search.

5 Conclusion

In this paper, we implement a single node indoor localization system based on MUSIC algorithm. Moreover, we improve the conventional MUSIC algorithm in three aspects. Firstly, a phase error elimination method is proposed in this paper. For the linear and nonlinear phase error, the interpolation method and the least squares scheme are proposed, respectively. Secondly, for the low spatial resolution problem in the conventional single point WIFI positioning system, we use a frequency band splicing technology to expand the spectrum width. Finally, this paper reduces the computational complexity of the conventional MUSIC algorithm. A direct search algorithm is proposed, which decomposes the two-dimensional spatial spectrum into angle spatial spectrum and time spatial spectrum. This method avoids two-dimensional search. Moreover, we further reduce the computational complexity of one-dimensional spatial spectrum by using Root-MUSIC algorithm and ESPRIT algorithm.

The simulation result shows that the phase error elimination method can effectively eliminate the phase error of channel state information. The measurement results in various indoor scenes and the simulation results on the MATLAB platform show that the system can achieve a positioning error of 2.7 m. Compared with conventional algorithm, the computational complexity of the proposed algorithm is reduced by 70% while the positioning accuracy is reduced by less than 0.2 m.

Acknowledgment. This topic is from the Heilongjiang Provincial Science Fund Project. Project Name: High-precision single-point indoor positioning theory and method based on OFDM-MIMO (No. ZD2017013) and from the national Science Fund Project: Wide-area space-based broadband wireless communication theory and air-ground multi-beam high-throughput transmission method (No. 61871155).

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